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1 **PROGRAMMABLE GRAY-SCALE LIQUID CRYSTAL DISPLAY**

2 Cross Reference to Related Applications

a 3 This application is a <sup>continuation-in-part</sup> continuation under 37 CFR 1.53 of  
4 co-pending U. S. Patent Application Serial no. 08/301,170,  
5 "Electrically Addressable Silicon-On-Sapphire Light Valve", R.  
6 L. Shimabukuro et al.

7 Background of the Invention

8 The present invention relates to liquid crystal displays  
9 formed on silicon-on-sapphire. More specifically, but without  
10 limitation thereto, the present invention relates to a liquid  
11 crystal display integrated with electronic circuitry on the  
12 display to provide a programmable gray-scale and to compensate  
13 for nonuniform and non-operating pixels in the display.

14 Liquid crystal displays (LCDs) are used in a wide variety  
15 of commercial applications, including portable and laptop  
16 computers, wristwatches, camcorders, and television screens.

1 Inherent limitations of existing technology arise from the  
2 necessity of fabricating LCDs on transparent glass or quartz  
3 substrates which are not amenable to processing with high  
4 quality electronic materials.

5 The integration of drive circuitry with LCDs has improved  
6 reliability and reduced size and weight for portable  
7 applications, but has been limited to thin film transistor  
8 technology using, for example, amorphous ( $\alpha$ -Si) and  
9 polycrystalline (poly-Si) silicon deposited on glass and quartz  
10 substrates.

11 Lattice and thermal mismatch between layers and low  
12 temperature deposition methods used in thin film transistor  
13 technology result in a silicon layer with poor charge carrier  
14 mobility and crystallographic defects which are directly  
15 related to electronic device performance and limitations. A  
16 comparison of MOS technologies for active matrix LCDs is shown  
17 in the following table:

	POLY-TFT HT-CMOS	POLY-TFT MT-CMOS	$\alpha$ -Si:H NMOS	CMOS UTSOS
1. Substrate	fused quartz	hard glass	hard glass	Al <sub>2</sub> O <sub>3</sub>
2. Max. process temp	~1000°C	600°C	300°C	1000°C
3. Threshold (Volts)(n-chnl)	2.0	2.0	1.5	0.5
4. Mobility	100	40	0.75	380
5. Shift register	20 MHz @15V	5 MHz @15V	0.1MHz @15V	>100MHz @5V
6. Integrated LSI logic	N/A	N/A	N/A	yes

1           For ultra-high resolution display applications, the high  
2           density of LSI circuitry is of particular importance for  
3           integrated displays. Compatibility with Very Large Scale  
4           Integration (VLSI) allows integration on-chip of video drivers,  
5           digital logic, compensating or fault-tolerant circuitry, and  
6           other computational circuitry, thereby providing greater  
7           functionality, higher reliability, and improved performance. A  
8           need thus exists for a material quality that overcomes the  
9           problems which occur in small scale, high density circuitry  
10          fabricated in  $\alpha$ -Si and poly-Si.

11          A need also exists for multiple level gray-scale and color  
12          displays for the applications mentioned above. Color displays  
13          have been made with colored filters by incorporating dyes into  
14          a guest host matrix, or by using field sequential color  
15          techniques. Color liquid crystal displays may also be made  
16          using the gray-scale properties of a liquid crystal display to  
17          achieve variations in color.

18          While the optical, electrical, and electro-optical  
19          properties of the liquid crystal material primarily determine  
20          the gray-scale properties, the substrate plays a significant  
21          role in the pixel uniformity of the display. Substrate warpage,  
22          or variations in surface morphology, can lead to variations in  
23          thickness of the liquid crystal layer. This in turn may lead to  
24          a nonuniform display intensity for a given pixel voltage, which  
25          is a problem for multiple gray-scale displays, high density

1 displays, and displays having stringent operating requirements.  
2 Furthermore, for high brightness displays, substantial heating  
3 may occur which can not be readily dissipated through  
4 substrates such as glass or quartz.

5 Prior research on brightness nonuniformity of LCDs  
6 established another cause of display nonuniformity,  
7 specifically the high resistance of narrow electrodes in high  
8 density LCDs.

9 A related problem particularly important for displays  
10 having stringent specifications is fault tolerance, or  
11 recovering from failed pixels. This problem is not emphasized  
12 in an LCD market primarily interested in low cost commercial  
13 applications, but becomes significant in high-reliability  
14 technology.

15 Another problem is that as display resolutions increase,  
16 the number of switching elements required in active matrix  
17 displays increases. A higher number of switching elements  
18 causes yield problems in manufacturing and in reliability.  
19 Fabrication yields of nonlinear switching elements (thin film  
20 transistors or diodes) may be improved by redundancy, but the  
21 redundancy applies only to the switching element rather than  
22 for the entire pixel.

Summary of the Invention

The programmable gray-scale LCD of the present invention is directed to overcoming the problems described above, and may provide further related advantages. The following description of a programmable gray-scale LCD does not preclude other embodiments and advantages of the present invention that may exist or become obvious to those skilled in the art.

A programmable gray-scale liquid crystal display comprises a polarizer operably coupled to a beam of incident light to pass a beam of polarized light having a polarization axis. A sequence of liquid crystal display pixels serially aligned with the beam of polarized light controls the angle of the polarization axis. An analyzer passes a gray-scale portion of the beam of polarized light from the sequence of liquid crystal display pixels corresponding to the angle of the polarization axis. Each pixel in the sequence may be independently programmed to vary the angle of the polarization axis for calibrating the display to a standard gray-scale and for correcting faulty pixels with VLSI on-chip driver and interface circuits.

One advantage of the programmable gray-scale LCD is that it provides a gray-scale with high resolution.

Another advantage is that multiple level gray-scale and color displays may be made according to the present invention.

1           Still another advantage is that failed pixels may be  
2           corrected by reprogramming the display.

3           Yet another advantage is that the gray-scale of the  
4           display may be programmed to conform to a gray-scale standard.

5           Another advantage is that a plurality of liquid crystal  
6           pixels are concatenated to form a display having a gray-scale  
7           that is programmable and fault-tolerant.

8           The features and advantages summarized above in addition  
9           to other aspects of the present invention will become more  
10          apparent from the description, presented in conjunction with  
11          the following drawings.

12                           Brief Description of the Drawings

13          Fig. 1 is a diagram of an example in the prior art of a  
14          liquid crystal display pixel in the non-transmissive or OFF  
15          state.

16          Fig. 2 is a diagram of the liquid crystal display pixel of  
17          Fig. 1 in the transmissive or ON state.

18          Fig. 3 is a diagram of the liquid crystal display pixel of  
19          Fig. 1 with gray-scale control.

20          Fig. 4 is an exploded view diagram of a programmable gray-  
21          scale LCD of the present invention.

22          Fig. 5 is a flow chart of the method of the present  
23          invention for fabricating the LCD of Fig. 4.

1           Fig. 6 is a block diagram of an optical testbed used for  
2 programming the LCD of Fig. 4.

3           Fig. 7 is a flow chart of gray-scale calibration  
4 programming of the LCD of Fig. 4 in the test bed of Fig. 6.

5           Fig. 8 is a flow chart of fault tolerance programming of  
6 the LCD of Fig. 4 in the test bed of Fig. 6.

7                           Description of the Invention

8           The following description is presented solely for the  
9 purpose of disclosing how the present invention may be made and  
10 used. The scope of the invention is defined by the claims.

11           Figs. 1-3 are diagrams illustrating an example of liquid  
12 crystal display (LCD) gray-scale as currently practiced. In  
13 Fig. 1, a liquid crystal medium 10 is contained within  
14 transparent electrodes 12 to form a pixel element 14. Pixel  
15 element 14 is then placed between a polarizer 16 and an  
16 analyzer 17. Analyzer 17 polarizes light in a direction  
17 orthogonally oriented with polarizer 16. When unpolarized light  
18 from a light source 22 passes through polarizer 16, transparent  
19 electrodes 12, and liquid crystal medium 10, the light becomes  
20 polarized and is absorbed by analyzer 17. Pixel element 14  
21 consequently appears OFF or opaque.

22           In Fig. 2, closing a switch 20 causes the application of a  
23 voltage V from a voltage source 18 to transparent electrodes

1 12. Voltage V causes the orientation of liquid crystal medium  
2 10 to change, which rotates the polarization axis of the light  
3 from light source 22 passing through polarizer 16. The rotated  
4 polarization axis allows the light to pass through analyzer 17.  
5 Pixel element 14 consequently appears ON or transparent.

6 In Fig. 3, voltage V is varied to vary the rotation of the  
7 polarization axis of the light from light source 22. The  
8 percentage of light from light source 22 passing through  
9 analyzer 17 may thus be controlled, resulting in a gray-scale  
10 varying from transparent to opaque. Typical LCDs are fabricated  
11 from a plurality of pixel elements 14, usually in a two-  
12 dimensional array or display area. A variation of this concept  
13 includes the design of pixel elements in a liquid crystal  
14 medium that are in the OFF state or opaque when there is no  
15 voltage applied to the transparent electrodes. Another  
16 variation uses bistable ferroelectric liquid crystals (FLCs),  
17 which have a continuously variable polarization with  
18 application of a voltage. FLC's may exhibit a gray scale by  
19 rapidly switching the pixels to allow a time averaged optical  
20 state which corresponds to a gray level. When used for color  
21 generation, the FLC pixel switching is correlated with the  
22 desired wavelength of light. This method is referred to as  
23 field sequential color.

24 The embodiment described herein pertains to nematic liquid  
25 crystals, however FLC's, supertwisted nematic, and the like may



1 also be used to practice the present invention.

2 Fig. 4 is a diagram of a fault tolerant, programmable  
3 gray-scale LCD 40 of the present invention with silicon-on-  
4 sapphire (SOS) technology to provide the advantage of VLSI  
5 compatibility. In this exploded view, spacers 44 form a cavity  
6 between SOS wafers 42. Pixel element electrodes are formed in  
7 SOS wafers 42A, 42B, and 42C. SOS wafers 42A, 42B, and 42C are  
8 referred to collectively as SOS wafers 42. The cavity formed by  
9 SOS wafers 42 and spacers 44 are filled with an appropriate  
10 liquid crystal material 10, such as nematic, supertwisted  
11 nematic or ferroelectric liquid crystals, and interposed  
12 between SOS wafers 42. Exemplary techniques for fabricating SOS  
13 wafers 42 are described by S. S. Lau et al in U.S. Patent  
14 ✓ 4,177,084, "Method For Producing a Low Defect Layer of Silicon-  
15 on-Sapphire Wafer", incorporated herein by reference thereto.  
16 SOS wafers 42 provide drive control and pixel electrodes for  
17 liquid crystal material 10. Each of SOS wafers 42 may be  
18 fabricated independently and joined in the final steps of  
19 fabrication. The combination of spacers 44 and SOS wafers 42  
20 results in a serial arrangement of pixels in optically coupled  
21 independent displays. The pixels may be individually programmed  
22 to calibrate a uniform gray-scale and to provide redundancy for  
23 replacing faulty pixels. *INS*  
*CI* *OK* *CI* *BS*

24 Fig. 5 is a flow chart of the process for fabricating LCD  
25 40. Portion "A" lists the order of steps in the fabrication of

1 SOS wafers 42 comprising the integrated drive control and pixel  
2 electrode circuitry. The drive control electronics may include  
3 circuitry to detect failure conditions in the display, to  
4 calibrate the display gray-scale, or to switch to alternative  
5 pixel configurations for replacing defective pixels. The  
6 circuitry need not be identical on each of SOS wafers 42, but  
7 preferably includes common drive and interface circuitry.  
8 Portion "B" of Fig. 5 describes the fabrication of the pixel  
9 electrodes on SOS wafers 42A and 42C and insertion of spacers  
10 44.

11 Portion "C" of Fig. 5 lists the order of steps for  
12 fabricating the pixel electrodes on SOS wafer 42B.

13 Portion "D" of Fig. 5 lists the order of steps for joining  
14 SOS wafers 42 and spacers 44 to form LCD 40.

15 Referring now to Figs. 4 and 5, SOS wafers 42A and 42C in  
16 Fig 4 are formed of device quality silicon-on-sapphire. Well  
17 known techniques are used to form VLSI circuitry (not shown) in  
18 the steps of isolation photo and etch, channel implant, gate  
19 oxidation, poly deposition and doping, gate definition,  
20 source/drain implant and annealing, oxide deposition and  
21 contact etch, metal deposition, patterning, and sintering, and  
22 deposition and patterning of passivation oxide. The VLSI  
23 circuitry may be formed on SOS wafers 42 outside of a display  
24 region 11.

25 A transparent conductor, such as indium tin oxide, tin

1 oxide, or polysilicon is deposited on substrates 42A and 42C in  
2 display region 11 and pixel electrodes (not shown) are  
3 patterned according to well known techniques. Spacers 44,  
4 schematically shown in Fig. 4, are then attached to substrates  
5 42B and 42C. Spacers 44 may be, for example, glass beads  
6 randomly distributed on the substrate.

7 A transparent conductor is deposited on opposite sides of  
8 a polished blank sapphire wafer or alternately glass, quartz or  
9 other transparent material to form SOS wafer 42B. The  
10 transparent conductor may then be patterned and formed into  
11 pixel electrodes (not shown).

12 Spacers 44 are inserted to form cavities on SOS wafers 42.  
13 The cavities are then filled with liquid crystal material 10.  
14 The pixel elements on each of display regions 11 of SOS wafers  
15 44 are serially aligned to form pixel sequences, and SOS wafers  
16 42 and spacers 44 are assembled into a single structure. The  
17 assembly of LCD 40 is completed with the addition of polarizer  
18 16 and analyzer 17 of Fig. 1 using techniques well known to  
19 those skilled in the art.

20 LCD 40 may be programmed and calibrated in an optical test  
21 bed 70 as shown in the block diagram of Fig. 6. A light source  
22 702 transmits a beam of light having a spatially uniform  
23 intensity pattern through intensity homogenizing and projection  
24 optics 704 to LCD 40. The light passed by LCD 40 is focused by  
25 imaging optics 706 and measured by an optical detector 708.

1 Programming electronics 710 adjusts programming voltages  $V_1$  and  
2  $V_2$  to vary the gray-scale to a desired value as measured by  
3 optical detector 708 for each pixel sequence of LCD 40.

4 Fig. 7 is a flow chart of a program for calibrating LCD 40  
5 to a standard gray-scale. LCD 40 is placed into optical test  
6 bed 70 of Fig. 6 and subjected to light from light source 702.  
7 Voltage  $V_1$  is applied to a pixel of one of the independent  
8 displays of LCD 40 corresponding to a gray-scale or color  
9 value. The percentage of light passed through the selected  
10 pixel is measured by optical detector 708 and compared to a  
11 standard. If the measured value is within tolerance of the  
12 standard value, voltage  $V_2$  is fixed to maintain the calibrated  
13 pixel intensity and voltage  $V_1$  is applied to another pixel  
14 sequence. If the measured value lies outside the tolerance of  
15 the standard value,  $V_2$  and/or  $V_1$  may be adjusted to vary the  
16 percentage of light passed to optical detector 708 until the  
17 measured value is within tolerance. Each row and column of LCD  
18 40 may be calibrated in a similar manner. After LCD 40 has been  
19 calibrated for one gray-scale level or color, another level or  
20 color is selected and the calibration is repeated until all  
21 rows and columns of LCD 40 are calibrated for all gray-scale  
22 levels or colors of the standard.

23 Fig. 8 is a flow chart of a program for correcting faulty  
24 pixels. LCD 40 is placed into optical test bed 70 of Fig. 6 and  
25 subjected to light from light source 702. While Voltage  $V_1$  is

1 applied to a pixel in a pixel sequence of LCD 40, the light  
2 passing through the pixel is measured and compared with a  
3 standard value. If the measurement falls outside the  
4 specification tolerance, voltage  $V_2$  is applied to another pixel  
5 in the pixel sequence. Voltage  $V_2$  is then adjusted in  
6 increments until the measured light passing through the pixels  
7 falls within the specified tolerance. Once the desired value is  
8 achieved,  $V_2$  is fixed for the corresponding pixel. Each pixel  
9 in the display area may be similarly calibrated.

10 Monolithically integrated, i.e. on-chip, VLSI circuitry  
11 may be fabricated according to well-known techniques outside  
12 region 11 of SOS wafers 42 in Fig. 4. The VLSI circuitry may  
13 include memory circuits such as static random access memory  
14 (SRAM), dynamic RAM (DRAM), and non-volatile RAM (NVRAM) to  
15 store the calibration information obtain through the processes  
16 described in Fig. 7 and Fig. 8.

17 Other modifications, variations, and applications of the  
18 present invention may be made in accordance with the above  
19 teachings other than as specifically described to practice the  
20 invention within the scope of the following claims.